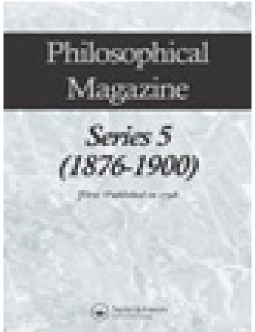

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I. *Contributions to the Theory of Luminous Flames.* *By* Dr. Karl Heumann *.

UNTIL lately Davy's theory of luminous flames sufficed to explain all observed phenomena; but recently our knowledge has been enriched by a series of observations which cannot be well brought into accordance with generally accepted notions.

For example, the observation of Frankland that the flames of hydrogen and carbon monoxide become luminous when these gases are burned under pressure, is opposed to the former view that the luminosity of flame is caused by the presence of solid particles which become intensely heated. Knapp's experiment, showing that the luminosity of a flame may be diminished, not only by admitting air, but also by a due admixture of nitrogen or carbon dioxide, cannot be explained on the supposition of an oxidation of the carbon previously suspended in the burning gas. For these and other reasons, Davy's theory must either be altered or replaced by a new hypothesis. The latter course does not appear to me to be required. In the following contributions I shall endeavour rather to develop this theory than to overthrow it. The genius of Davy is made apparent when we find that the discovery of so many facts since his day has in no way overthrown his theory, but has only rendered a development of it necessary in order to bring it into keeping with an advancing science.

* From Liebig's *Ann. der Chemie*, vol. clxxxi. part 2, pp. 129–153, and vol. clxxxii. pp. 1–29. Translated by M. M. Pattison Muir, the Owens College, Manchester.

I have generally in my remarks adopted a chronological arrangement of the various researches, because it is only thus that the course of thought which I have followed can be logically represented. A systematic arrangement would, it is true, place the simpler before the more complex conditions; but in the present case the latter, which occur chiefly in the case of luminous carbon-containing flames, are the more important and have been more studied.

The experience gained from the study of flames burning under complex conditions is tested and applied in the case of simpler flames, and so becomes a guide to the explanation of the conditions affecting luminous flames in general.

Diminution and Restoration of Luminosity in Hydrocarbon-flames.

In the greater number of researches which have hitherto been conducted upon the luminosity of flames, those flames have been principally examined the luminosity of which is to be ascribed to the presence of carbon, and methods of research in which the luminosity has been either increased or diminished have, for the most part, been adopted.

Such methods are open to many objections, the principal of which (viz. the introduction of various agencies acting now in this way, now in the opposite, during the same experiment) has been too much overlooked. By reason of this oversight, researches, leading to diametrically opposed conclusions, have been published; and since Davy's theory is no longer of universal application, we have been left without any means of bringing the facts concerning luminous flames into harmony with one another.

Frankland has broached the hypothesis that the luminosity of flame is not due to particles of suspended carbon, but is caused by the vapours of heavy hydrocarbons which radiate white light. Strong positive evidence in support of a view so much at variance with the generally accepted theory, could hardly be expected; and Frankland has relied principally upon the fact that we are acquainted with many luminous flames in which we cannot suppose that solid matter is present.

To the instances already known Frankland has added the interesting observation that hydrogen and carbon monoxide when burned in oxygen under a pressure of 10 to 20 atmospheres, yield a luminous flame affording a continuous spectrum, and also that the faintly luminous flame of alcohol becomes as bright as that of a candle when the pressure is increased to 18 or 20 atmospheres*. These experiments are

* Compare L. Cailletet, *Compt. Rend.* clxxx. 487.

not so convincing as might at first sight appear, inasmuch as we know that the temperature of the flame is increased at high pressures *, and also that at the temperature of the electric spark many gases yield a continuous in place of a line spectrum. The power of gases as regards emission of light also varies considerably under these circumstances; and it does not appear that we are absolutely necessitated, as Frankland has supposed, to ascribe the increase in luminosity to the increased density of the gas, although doubtless this circumstance is not without considerable influence.

The inquiry as to the nature of hydrocarbon-flames is quite independent of the meaning which we may attach to these appearances; and if Frankland puts forward the above-cited phenomena of combustion as analogies to guide him in views concerning carbon-flames, no very forcible argument can be really deduced from the examples, because, as W. Stein † has pointed out, it cannot be shown that the reaction in luminous carbonaceous flames *must* be an analogous one to that described above.

Frankland's declaration that the soot must be regarded as an accumulation of heavy hydrocarbons whose vapours are condensed on the cold body brought into the flame, may be regarded as almost confuted by Stein's objection that in this case the soot must become gaseous at higher temperatures (which is not the case).

New doubts arise concerning the prevailing theory when we consider that the admixture not alone of air, but also of nitrogen, carbon dioxide, or other completely indifferent gases, with coal-gas causes a great decrease in the luminosity of the flame of that gas. Hence we cannot trace the decrease in luminosity solely to the more energetic oxidation of carbon contained in the flame.

The experiments of Stein ‡ and R. Blochmann § allow us to suppose that, the particles of carbon being more widely separated by the admixed gases, the oxygen of the air is able to oxidize them to carbon monoxide more quickly than under the ordinary circumstances of combustion.

To the theory of these authors, viz. that diminution of luminosity is a consequence of dilution, Wibel ‖ opposes the view that the absorption of heat brought about by the admixture of an indifferent gas is the sole cause of decrease in

* Ste.-Claire Deville, *Compt. Rend.* lxvii. 1089.
† *J. pract. Chem.* [2] viii. 401. ‡ Ibid.
§ Lieb. *Ann.* clxviii. 355.
‖ *Deut. chem. Ges. Ber.* viii. 226.

luminosity. Wibel was led to this view by considering the fact that a mixture of coal-gas and air, nitrogen, or carbon dioxide, which burned with a blue flame, became luminous and burned with a smoky flame when the tube from which the mixture issued was strongly heated. In this case the dilution must have been increased by the increase of temperature ; nevertheless the flame became luminous.

In order to convince one's self of the justness of the conclusions which are drawn from this observation, it is necessary to examine somewhat closely the method adopted by Wibel in his investigation. He says, "A tube of platinum, 8 to 10 centims. in length, is attached to an ordinary Bunsen's burner which is closed at the bottom; the gas to be burned is brought into the burner by means of a tube soldered to the lower part; when the flame of the burning gas has been adjusted to the proper point, the indifferent gas is admitted until the flame is rendered non-luminous ; the platinum tube is then heated by means of two non-luminous Bunsen flames held horizontally on either side of the tube, so as to ensure that it be equally heated . . . . The same appearance is noticed in the case of the ordinary Bunsen flame, rendered non-luminous by admixed air, when the platinum tube is placed in the opening of the lamp and is heated."

The last mentioned experiment, as described by Wibel, must be controlled before one can justly identify the diminution of luminosity in the Bunsen burner with Knapp's experiments upon diminution. Some time ago Barentin * showed that the amount of luminous gas which enters a given space is very different according as the gas is or is not ignited. Barentin believed that the explanation of the smaller amount of gas entering a burning lamp was to be found in the counter pressure exercised by the burning, and therefore expanding gas, upon the entering gas. Blochmann † showed that the diminished consumption of gas was to be traced solely to the increase of volume caused by the gas passing over the heated upper part of the burner.

The fact that a mixture of gases issuing from a Bunsen lamp through a strongly heated tube burns with a luminous flame, may therefore be due to causes other than that put forward by Wibel, viz. rise in temperature of the flame ; for it is evidently an improbable supposition that the consumption of gas, and therefore also the quantity of air (or other gas) drawn into the burner, will be unaffected by the passage of the gas over a glowing tube ; and so also it cannot, *à priori*, be expected that the proportion between air and gas will re-

* Pogg. *Ann.* cvii. 183. † *J. für Gasbeleuchtung*, v. 355.

main the same when the mixture is passed over a hot as when it is passed over a cold tube.

I was therefore compelled to alter the conditions of experiment in order to render void that particular effect of the hot tube which has just been described.

If rise of temperature of the flame is the cause of increased luminosity, the effect must be the same if one heats, not the gaseous mixture, but only the indifferent gas. This experiment may be readily carried out with a Bunsen's burner, through the two air-tubes of which are passed small platinum tubes about 7 centims. in length; the outer openings of these tubes are narrowed so that a quantity of air just sufficient to bring about complete non-luminosity is allowed to enter.

A thin-walled glass tube, the upper rim of which is covered with platinum, may, with advantage, take the place of the ordinary metal tube of the Bunsen's lamp; the latter tends to cool the heated air to too great an extent. On lighting the gas issuing from the glass tube it burns with a non-luminous flame; but on strongly heating the two platinum tubes by means of Bunsen's burners (care being taken that the products of combustion do not enter the platinum tubes) the flame becomes luminous.

It might be supposed that this fact is to be explained on the supposition that the volume of air passing over the platinum tubes is unaltered by heating these tubes, but that the true quantity of air calculated for equal temperatures is much smaller when the tubes are hot, and that there is therefore a deficiency in the amount of oxygen required to completely burn the carbon, and so to maintain the flame in a non-luminous state.

In order to show that this supposition is untenable, and that the increase in luminosity is to be ascribed solely to the rise in temperature of the flame, the experiment must be modified. Coal-gas and air, or carbon dioxide, are mixed in a gasometer in such proportions that, when conducted through a platinum tube about 10 centims. in length and 8 millims. in width, the mixture burns with a clear blue flame. If the platinum tube be heated to redness, the flame becomes nearly as luminous as that of ordinary coal-gas. On allowing the platinum tube to cool, the flame again becomes non-luminous.

From this experiment the conclusion is evidently to be drawn that it is *the added heat alone* which has caused the flame to become luminous, inasmuch as a diminished supply of air cannot in this case, as in the former, have influenced the result.

It remains, however, to be investigated whether the gaseous mixture, burning with a luminous flame in consequence of the application of heat, has or has not been altered so that its luminosity shall continue when it has been allowed to cool to the ordinary temperature. In other words, if the increase in luminosity is directly due to increase in temperature of the flame, and is not brought about by a chemical change in the gaseous mixture, then the flame which appeared luminous at the point of the strongly heated tube should again become non-luminous when the gaseous mixture is cooled, after having passed through the heated tube, and is then ignited.

This experiment may be carried out by connecting two glass tubes by means of gypsum to the platinum tube, the outer glass tube being V-shaped and being surrounded by cold water. If the mixture of gases be passed through this arrangement, the platinum tube being strongly heated, and be ignited at the orifice of the glass V-tube, a non-luminous flame is noticed; whereas if the V-tube be removed and the gases be ignited at the orifice of the platinum tube, the flame becomes luminous. More simply, the experiment may be carried out by burning the gaseous mixture as it issues from a platinum tube about 12 or 15 centims. in length: in heating this tube near to its orifice the flame becomes luminous; but on heating the tube at a point further back the luminosity of the original flame is not increased, because the heated gases are again cooled by passing over the outer part of the platinum tube.

In employing a mixture of air and coal-gas under certain conditions, it is found, as Wibel has noticed, that "the gas aspirated from the opening of the burner reveals—by the amount of water and carbon dioxide which it contains, as also by its burning with a luminous flame under the ordinary conditions"—that a partial decomposition has taken place.

While Wibel noticed a not inconsiderable deposition of carbon when air and coal-gas were passed through a red-hot platinum tube, in my experiments, in which the air only was passed through a heated platinum tube, no such deposition was noticed in the glass tube, at the orifice of which the gases burned with a luminous flame for a considerable length of time. In Wibel's case the deposition of carbon was doubtless due to a too great local heating of the platinum tube through which the gases were passed. Such an intense heating is not necessary in order to attain the aim of the experiment. From that experiment in which the flame of a gas, previously rendered non-luminous, was restored to luminosity by means of heat, Wibel draws very far-reaching conclusions. He rejects the deductions of previous experimenters; but in doing so he rushes too far to the opposite extreme. For example, he believes himself justified in concluding:—

"1. Decrease in luminosity *cannot* be due to dilution of the gases, whether understood in Frankland or Blochmann's meaning of the term, inasmuch as in the above mentioned researches such dilution was at any rate increased by heating, yet the flame became luminous."

"2. Decrease in luminosity, in Knapp's experiments, as also in the case of the ordinary Bunsen's flame, is much more to be traced to the *cooling effect*, on the interior of the flame, of the entering gas. By heating the latter the flame becomes luminous."

Wibel finds "a most noteworthy argument" in favour of these two points in the peculiar behaviour of the flame of coal-gas and oxygen.

On the one hand, this flame becomes non-luminous only when the current of oxygen is rapid, and when the flame is cooled by metallic gauze; on the other hand, by proper treatment the flame may be made a source of intense light. These circumstances show, according to Wibel, that neither dilution nor oxidation is a cause of decrease of luminosity. By similar reasoning it might be shown that Wibel's theory is itself erroneous. Everyday experience tells us that the blue flame of Bunsen's burner, as well as that of the blowpipe, possesses a much higher temperature than the ordinary luminous flame; but if Wibel be correct in saying that decrease of luminosity is a consequence of cooling only, then, logically, the temperature of the luminous flame ought to be higher than that of the non-luminous flame.

Those flames whose luminosity is decreased by means of air might perhaps not be classed with those in which a similar result is brought about by means of indifferent gas; but little would thus be gained, for the Bunsen's flame behaves, so far as its power of becoming luminous is concerned, similarly to Knapp's flame, the only distinctive point (the higher flame-temperature consequent upon the entrance of oxygen in the admitted air) not being proportionately altered by heating the tube of the burner, the flame nevertheless becoming luminous.

But while, in the case of flames rendered non-luminous by indifferent gases, it might be supposed that the heat gained when the tube of the burner is warmed merely serves to replace that lost by absorption into the entering inert gas (which heat had formerly caused luminosity), this supposition is contradicted by the already cited analogous case of decrease of luminosity by means of air, inasmuch as it cannot be supposed that there is a withdrawal of heat from the luminous material in the flame, the temperature of which is greatly increased.

In experiments upon decrease of luminosity caused by completely indifferent gases free from oxygen there will, of course, be a considerable decrease in temperature, because a fixed quantity of heat must be divided throughout a larger volume of gas.

W. Stein *, however, has pointed out that in these cases a cause other than lowering of temperature is at work. He shows that a flame rendered non-luminous by means of nitrogen yet possesses so high a temperature that it is able to decompose, with deposition of carbon, coal-gas conducted in a glass tube through it; he also observes that an inflammable gas, carbon monoxide, whose pyrometric effect is nearly as great as that of coal-gas, causes the flame of the latter gas to become non-luminous. In order to bring about the complete non-luminosity of 1 volume of coal-gas, there is required 1·6 volume in Bunsen's burner, and 0·9 volume in Brönner's burner, of carbon monoxide.

In this case decrease in luminosity is not accompanied by a real decrease in the temperature of the flame; and we are obliged to allow that dilution of the burning gas plays an important part, and may *of itself*, independently of any absorption of heat (which often takes place simultaneously) cause decrease in luminosity.

Wibel's experiment does not prove, as that author supposes it to do, that cooling of the interior of the flame is the sole cause of decreased luminosity, because the flame is simultaneously altered in its composition, *i. e.* it is largely diluted by the entering gas.

We find, then, some of those observers who have been already mentioned tracing decreased luminosity, brought about by admixed gases, *solely to the diluting action* of these gases; we find Wibel, on the other hand, tracing this decrease *solely to the cooling action* of these gases; but it appears to me that the truth lies between these two conflicting views.

It is difficult to devise experiments in which two or more causes tending to decrease luminosity are not simultaneously at work; and yet every thing depends upon our being able sharply to distinguish between these various causes. It will only be possible to gain a clear knowledge of the processes going on in flames when we are able to separate these processes and to study each alone.

It appeared to me necessary to devise an experiment in support of the well-known statement—the luminosity of a flame is diminished by cooling—which should admit of no other interpretation than this.

By the following method I have been able to show that

* *J. pract. Chem.* ix. 183.

cooling a flame is of itself capable of bringing about decrease of luminosity, and that luminosity may be then restored by simply applying heat; the result cannot be called in question by supposing dilution or oxidation to have taken place.

A luminous gas-flame, 3 to 4 centims. in length, proceeding from the point of a blowpipe or other narrow tube, is allowed to play horizontally upon a platinum basin suspended in a vertical position, so that the flame may broaden out and become blue. In this well-known experiment decrease of luminosity must not be traced solely to withdrawal of heat by means of the metal, inasmuch as the broadening out of the flame enables oxidation and dilution, as well as cooling, to influence the result.

If the platinum basin be now heated, on the side opposite to that on which the flame impinges, by means of a Bunsen's lamp held horizontally, the gas-flame becomes more and more luminous as the temperature of the basin increases, until it finally is restored to its original degree of luminosity. Of course the metal must be perfectly pure, and must not be touched with the fingers before the experiment; else the flame will be coloured yellow.

It is here shown that luminosity of the flame, which had been diminished by the use of the platinum basin, is restored solely by raising the temperature.

If the Bunsen lamp be removed, the flame quickly decreases in luminosity until it becomes blue.

In *this* experiment, in which decrease of luminosity is brought about by lowering the temperature, the objection formerly raised—viz. that the broadening out of the flame complicated the result—can no longer be maintained, inasmuch as the small decrease of volume consequent upon the cooling would tend to produce an opposite result. It is therefore experimentally proved *that cooling a flame is itself sufficient to cause a decrease in the luminosity of that flame.*

Reasons have been already given which oblige us to acknowledge that *dilution* of a flame by admixed gases is of itself sufficient to cause decreased luminosity * (Bunsen's flame, decreased luminosity by carbon dioxide); and inasmuch as the admission of a cold gas into a flame must withdraw heat from that flame, it is concluded *that the decrease in the luminosity of carbon-containing flames brought about by*

* Frankland has observed that decrease of luminosity of carbon-containing flames is a consequence of dilution by lowering of atmospheric pressure; and he has concluded that the decrease of luminosity is connected with the decrease of pressure. I have not cited this experiment in proof of the effect of dilution in decreasing luminosity, because lowering of temperature is associated with lowering of pressure, and this must have an influence in decreasing the intensity of the light.

admitting indifferent gases is due to dilution, and also to lowering of the temperature of the flame by these gases.

The fact that a flame which has been rendered non-luminous by means of indifferent gases may be again rendered luminous by heating the tube of the burner, I hope to explain by establishing the following points.

A flame formed of coal-gas and an indifferent gas or air, and burning blue, requires, in order to cause it to become luminous, a higher temperature than that which is possessed by the luminous undiluted flame. The flame of a Bunsen's burner in which non-luminosity has been brought about by means of air is very hot, but becomes luminous when the temperature is much increased by heating the tube.

These points in the behaviour of the flame of coal-gas and oxygen, which Wibel adduced in support of his theory, are explained by me as follows. Blochmann and Wibel both noticed that the luminous flame of a Bunsen's lamp, fed with oxygen by one opening while the other is closed, can be rendered non-luminous only by employing a rapid current of oxygen and a cooling surface of metallic gauze, simply because the temperature of the flame, when pure oxygen is employed, is very high. The absorption of heat caused by the entrance of cold oxygen, as also the absolute rise in temperature required by the *gaseous mixture* in order that it shall become luminous, are entirely, or almost entirely, equalized by the intense heat produced by the combustion in pure oxygen. Therefore the production of non-luminosity is so difficult; that non-luminosity should be brought about only by employing a rapid stream of oxygen and a cooling metallic surface is self-evident.

It is known that a gas-flame may be caused to burn with great luminosity by the admission in proper quantity, and by a proper method, of pure oxygen. This fact certainly depends upon the production of a very high flame-temperature unaccompanied by such dilution as is noticed in the Bunsen's or blowpipe flame when air is employed, and when the diluting gas is nitrogen. In this experiment it is found that the greatest luminosity occurs when a rapid stream of oxygen is introduced, but that too great a quantity of oxygen, as too small a quantity, tends to decrease luminosity. Inasmuch as a much higher temperature might be reached by increasing the quantity of oxygen beyond that at which the maximum of light is evolved, it seemed probable that the actual action of this excess of oxygen in decreasing luminosity was not to be traced solely to its cooling and diluting the burning gas, as is the case with altogether indifferent gases, but that a third cause, perhaps more energetic than either of those just mentioned, was at work.

This supposition led to a more exact examination of the changes brought about in the flame of coal-gas by an excess of oxygen. When a flame, burning at the orifice of a wide tube, is placed in an atmosphere of pure oxygen, a notable increase in luminosity takes place within the flame-mantle, which is itself, nevertheless, considerably decreased in size, while the outer non-luminous border of the flame is broadened out. In order to study this action more narrowly, I have found it advantageous to make the flame very small by allowing the gas to issue from a narrow tube. If, for instance, a flame of coal-gas 4 to 5 centims. in length, issuing from a blowpipe-nozzle, be plunged into a reversed jar of oxygen, the appearance of the flame is greatly altered. The outer, scarcely visible, part of the flame increases enormously in size at the expense of the inner and luminous part. A small luminous point alone represents what was formerly a broad luminous band; at the same time, the whole flame decreases proportionately from what it had been in air. This is to be accounted for by the absence of diluting nitrogen, a circumstance which also causes the temperature of the flame to increase considerably. The decrease in luminosity can scarcely be traced to any other cause than the large quantity of pure oxygen, which, by diffusing inwards into the narrow flame, brings about an immediate oxidation of the contained carbon, which is, therefore, not necessitated to spread through the flame in a red-hot state in order to find oxygen sufficient for its combustion.

If this supposition be true, it follows that decrease of luminosity can only be brought about by combustion in oxygen in the case of those flames the light-giving constituent of which is capable of being converted by excess of oxygen into a feebly luminous gas, but that those flames the luminosity of which is due to some substance which cannot be transformed by oxygen into such a gas must continue to burn in oxygen, even when issuing from the *smallest* orifice, with brilliancy—that, indeed, an increase in luminosity must be brought about under such conditions, because of the increased temperature of the flame.

Direct experiment confirms these deductions, and therefore also the original supposition.

Hydrogen saturated with vapour of chromium oxychloride ($Cr_2O_2Cl_2$), and issuing from a blowpipe-nozzle, burns in oxygen with a dazzling white light: the luminosity is in this case due to the presence in the flame of chromium oxide. If the hydrogen be laden with the vapour of stannic chloride ($SnCl_4$), it burns, under the same conditions, with a blue flame of much greater brilliancy than when the combustion proceeds in ordinary air. The product of combustion is in this case also a solid, viz. stannic oxide.

In order to prove that a similar appearance is noticeable in the case of luminous vapours, in so far as these are not oxidized to non-luminous gases by excess of oxygen, hydrogen was conducted through a vessel containing common salt and zinc filings moistened with dilute hydrochloric acid (as in Bunsen's well-known experiment). The gas issued from a blowpipe-nozzle and burned with an intensely yellow flame, the luminosity of which was not decreased, but rather the reverse, when the flame was plunged into a vessel containing oxygen.

Inasmuch, therefore, as the decrease in luminosity which a small coal-gas flame suffers when burned in oxygen is due to the presence of an excess of the latter gas, the fact that this decrease does not take place to so marked a degree when the flame is burned in ordinary air is to be traced to the presence of inert nitrogen, which, by diluting the oxygen, diminishes the energy of the oxidation.

In order to prove the justness of this conclusion, the nitrogen in a given volume of air was replaced by carbon dioxide; *i. e.* a cylinder was filled over water with 1 volume of oxygen and 4 volumes of carbon dioxide; and, after carefully mixing the gases, a coal-gas flame, burning at the orifice of a small brass tube, was brought into the mixture. The flame continued to burn with a degree of luminosity equal to that which it exhibited in ordinary air; it follows, therefore, that the fact of dilution alone influences the result, the nature of the diluting gas being unimportant.

Every indifferent gas, including the products of combustion themselves, must exert a similar influence. When an ordinary flame, issuing from a fine orifice, is burned in oxygen, the luminosity decreases for the reason formerly assigned; but as soon as the products of combustion (water and carbon dioxide) accumulate sufficiently to dilute the oxygen considerably, the luminosity begins to increase. The flame which had been reduced to a luminous point becomes enlarged until it presents an appearance similar to that exhibited by it when burning in ordinary air; this happens at the moment when the oxygen in the vessel is diluted by the products of combustion to the same proportionate extent as it is diluted by nitrogen in the atmosphere.

If the combustion be continued beyond this point, the luminosity again decreases—not as was noticed in the former case, by a great decrease in the size of the flame-mantle, but by general weakening of the light until complete non-luminosity is attained. The flame then increases in size, and finally goes out.

This kind of non-luminosity exhibits a great resemblance to that noticed when the burning material is diluted by mixing with it indifferent gases, such as carbon dioxide and nitrogen; the causes of non-luminosity are indeed in both cases identical. Inasmuch as every ordinary flame (with the exception of the flames of explosive substances) requires for its existence two combustibles, the chemical union of which brings about the glowing of the gases, it follows that it is a matter of indifference which of the combustible materials is diluted by indifferent gases—the coal-gas for example in Knapp's experiments, or the oxygen of the atmosphere.

And in fact it may be shown that a gas burning with luminosity in ordinary air, burns with a blue flame when plunged into a mixture of 5 volumes of air with 2 volumes of carbon dioxide. This experiment is the converse of Knapp's; and, as in that case, decrease of luminosity is due to dilution, and cooling of the flame. Instead of diluting the air with carbon dioxide previously to the experiment, the products of combustion may be allowed themselves to bring about this dilution, the gas being burned in an inverted globe: it is then noticed that the flame quickly becomes less luminous and then burns blue, at the same time increasing in size.

The flame remains non-luminous and yet large, but again becomes luminous if transferred at the proper moment to the atmosphere; otherwise it goes out.

This experiment on decreased luminosity is perfectly analogous to that described in the case of a flame burning in oxygen; only in this instance nitrogen was absent, and the products of combustion were the sole diluents of the oxygen.

When a small gas-flame is plunged into an inclosed volume of oxygen there is noticed, then,

1. Decrease in luminosity of the flame, accompanied by increase in the size of the flame, the light from which is very small;

2. Increase in luminosity commences, and proceeds until the flame exhibits an appearance similar to that which it possesses in ordinary air, because the energetic oxidizing action of the pure oxygen upon the glowing matter in the flame is moderated by the diluting products of combustion;

3. A general decrease in luminosity ensues, but now by a lowering of the intensity of light of the whole flame, brought about by the increasing dilution of the oxygen by the pro-

ducts of combustion, and also by lowering of the temperature of the flame.

These two causes gradually increase, until the flame, which continually increases in size, becomes blue, then invisible, and finally, being cooled below the point of ignition, goes out.

Besides cooling and dilution of the carbon-containing flame, a third cause has been shown to influence the decrease of luminosity—viz. *the energetic destruction of the luminous material*, *i. e.* the oxidation of carbon to feebly luminous gases (carbon monoxide and dioxide).

Generalizing the results of the experiments upon the means by which flames which have become non-luminous may be again restored to luminosity, we find:—

1. That hydrocarbon flames which have lost their luminosity by withdrawal of heat again become luminous by the *addition of heat*.

2. That flames rendered non-luminous by dilution with air or indifferent gases become luminous by *raising their temperatures*.

3. That flames rendered non-luminous by excess of oxygen, which brings about energetic oxidation of the carbon, are again rendered luminous by *diluting the oxygen with indifferent gases*.

It would be very interesting to observe whether flames rendered non-luminous by admixture of indifferent gases may be again rendered luminous by heating the tube of the burner, the combustion being carried out under such pressures as would cause the molecules of the burning gases to maintain their original proximity to one another, notwithstanding the admixture of nitrogen or carbon dioxide. I have not myself the necessary apparatus at hand; but I would direct the attention of any chemist who is interested in these experiments upon luminous flames to the subject. It would also be well to note whether the decrease in luminosity suffered by a small gas-flame when burned in oxygen is maintained when the oxygen is diluted to one fifth or further.

If, in the case of previous observers, the point of dispute was whether cooling *or* dilution were the cause of decreased luminosity in carbon-containing flames when the combustible material was mixed with air or indifferent gas, to me it appears that there are at least *three* causes, each of which is capable of decreasing the luminosity of these flames, viz. *withdrawal of heat, dilution, and oxidation of the luminous material*.

In most cases two or all of these causes are at work:—in non-luminosity brought about by nitrogen and carbon dioxide, especially dilution and heat-absorption; in the widening out of the flame caused by a cold surface, absorption of heat and more rapid oxidation of carbon; and in non-luminosity caused by air, each of the three causes is at work.

In the latter case the presence of the oxygen of the admitted air tends to cause a rise in the temperature and a diminution in the size of the flame, circumstances which are opposed to the absorption of heat and dilution of the flame.

The flame of the Bunsen's burner appears to be the final product of a whole series of causes acting some in one direction, some in another; and it is not to be wondered at that observers of luminous flames have arrived at such diverse and contradictory conclusions, inasmuch as they have made the study of this flame their principal object, overlooking the great complexity of the conditions affecting it, instead of preceding such a study by an investigation of more simple instances of combustion.

Effect of Withdrawal of Heat upon Flames.

On account of the simpler conditions affecting so-called non-luminous flames I have considered these first, omitting all mention of changes in the intensity of light, until a study of the effect of the withdrawal of heat shall have given us some exact knowledge concerning this cause of decreased luminosity.

Distance between Flame and Burner.

In a paper of Blochmann's* the fact is noticed that a gas-flame does not touch the rim of the burner, nor a candle-flame the wick. Blochmann says:—"If a gas-flame be closely examined it is seen not to rest immediately upon the opening of the burner. In the case of a highly luminous flame the luminous portion presents too great a contrast to enable one to notice this fact with certainty; but by decreasing the quantity of gas the space between burner and flame becomes more apparent in proportion as the intensity of the light diminishes. The small semicircular non-luminous flame issuing from a bat's-wing burner when the supply of gas is small, may be arranged so that the space between the burner and the flame shall appear as great as the height of the flame itself."

This small intermediate space may be proportionately increased by mixing an indifferent gas, such as nitrogen or carbon dioxide, with the coal-gas before the latter is ignited. Blochmann also noticed that the intermediate space was increased by burning the diluted coal-gas under diminished

* Liebig's *Annalen*, clxviii. 345.

pressure; and he concluded that the cause of this increase was to be traced to the presence of the diluting gas. He supposed that there is a "momentary combustion taking place in the lowest part of every flame;" this can only be when the issuing gas is mixed with a due proportion of air; therefore Blochmann supposed that the explanation of the increased distance between flame and burner, which is observed to take place when coal-gas is diluted with an inert gas, was to be found in the following statement:—"The greatly diluted gas issuing from the burner at once becomes mixed with air. In order to maintain the constancy of the flame this mixture must contain a fixed quantity of combustible gas. But that this quantity may be maintained, in the case of a diluted gas, at the same point as if the diluting gas were absent, a much larger volume of the issuing gas must become mixed with the air; that is, the space between flame and burner must be increased."

The following facts are, I think, opposed to Blochmann's somewhat strained explanation. *Where a cold object touches the flame, a dividing space, similar to that noticed between flame and burner, is always observed.* The colder the object and the more diluted the burning gas, the greater is the observed space.

If a flame be diluted with a considerable excess of carbon dioxide, for example, a piece of thick metallic wire brought into this flame causes a clear space around itself, which increases in proportion to the amount of carbon dioxide present.

This experiment is best carried out in a darkened room: it is always difficult to distinguish the limits of the very slightly luminous flame, even if a dark background be employed.

These facts point to the conclusion that *withdrawal of heat* from the flame by means of the upper part of the burner is the cause of the observed vacant space, and that to the same cause (withdrawal of heat) is to be assigned the *extinction* of the flame in the neighbourhood of a cold object. The explanation of the increase in the distances between flame and burner, or cold object, brought about by the presence of diluting indifferent gases, is to be found in the fact that the presence of such gases lowers the flame-temperature, by causing a partition of the quantity of heat needed to maintain a given quantity of the coal-gas in a state of combustion throughout a greatly increased volume of gas. If the temperature of the flame be already low, the further decrease occasioned by the introduction of a cold body, although small in actual amount, is sufficient to cool a *considerable extent* of gas beneath the ignition-temperature: the flame is therefore extinguished in this cold space.

If this be the true explanation of the production of the observed vacant space, it follows that heating the object placed in the flame should cause a decrease in the extent of this space. The following experiments prove that this actually takes place.

A cold iron wire held in a non-luminous flame which has been diluted with an excess of indifferent gas, causes extinction of the flame throughout a considerable space around itself; but as the wire becomes hotter, this space gradually decreases in extent, until when the wire is raised to a red heat (either by the heat of the flame or by an extraneous source of heat), the flame is observed to rest upon the wire without any intervening space. Again, a mixture of coal-gas and carbon dioxide may be burned at the orifice of a platinum tube, so that a non-luminous flame, separated from the upper rim of the tube by a vacant space, is produced. If the platinum tube be now heated by means of a Bunsen's lamp near its orifice, the non-luminous flame spreads down throughout the formerly apparently empty space until it touches the platinum tube.

These experiments not only confirm the explanation already given, but they also completely exclude the possibility of any such cause as that suggested by Blochmann taking part, even to a subordinate extent, in the production of the space observed between the flame and the burner. For the experiments prove that a flame, even when largely diluted with indifferent gases, burns in contact with a heated burner; whereas an effect such as Blochmann imagined, tending to produce separation between flame and burner, although it might possibly be decreased, yet certainly could not be removed by heating the burner.

I therefore look on the following conclusion as perfectly just:—The fact that a gas-flame does not touch the ring of the burner, nor a candle-flame the wick—further, that a flame does not actually impinge upon a cold body placed within it, is caused by the withdrawal of heat from the glowing gas. The flame is cooled below its ignition-temperature; it ceases to glow and becomes invisible: the flame in the neighbourhood of a cold body is extinguished.

The experiment just described, which proved that a greatly diluted gas may be caused to burn in contact with the metallic burner when the latter is heated, leads us to inquire whether the action of the upper part of the burner in causing a separation between itself and the burning gas is not aided by the cold gas issuing from the centre of the burner, or, indeed, whether this cold gas is not of itself sufficient, under certain conditions, to produce the observed effect.

The temperature of the lower part of the flame is certainly not so high as that of the middle portions; and the cause of this fact might be sought for in the presence of unburned and comparatively cold gas, which afterwards becomes heated at the expense of the lowest flame-mantle. It has been already shown that the distance between the flame and any object in contact with it is increased so soon as the temperature of the flame is decreased by the admission of indifferent gas. The cold unburned gas in the ordinary flame plays the same part, in reference to the lowest part of the flame, as the indifferent gas in the above-cited example did towards the burning gas in general. That the action of this cold gas in increasing the space between flame and burner is not, however, very great, is evident from the fact that, in an ordinary burner the vacant space alluded to is no greater, or not much greater, than that noticed between the flame and a metallic rod held in the upper part of the burning gas.

The foregoing observations are only applicable in the case of flames which burn under moderate pressures, as the flames of our ordinary lighting apparatuses—gas-burners, oil and petroleum lamps, candles, &c. If abnormal pressures are employed, the phenomena presented by the flames are greatly altered: in place of a space measuring scarcely 2 millims. from burner to flame, there is noticed a distance of very varying magnitude, generally to be measured in decimetres, the production of which is to be ascribed to quite other causes than those operative in ordinary flames.

An experiment has long been known in which spirit of wine is confined in a strong brass vessel furnished with an exit-tube and stopcock, and is then boiled until, when the stopcock is opened, the spirit rises towards the ceiling of the room: on bringing a flame near the exit-tube, the spirit burns with a luminous flame only near the ceiling, the stream of issuing liquid appearing non-luminous.

By boiling spirit of wine in a copper vessel, and causing the vapour to issue through a glass tube drawn to a fine opening about 3 millims. in width, a long flame is obtained the base of which is separated by a distance of 10 or 12 centims. from the orifice of the glass tube. This distance is diminished by warming the exit-tube, or by holding a small rod in the issuing vapour and thereby decreasing its velocity. A small drop of alcohol soon gathers at the opening of the glass tube; if this be ignited by bringing a source of heat near it, or by causing the flame of the burning vapour to rush back by means of a rod held in the vapour, a small flame is produced which momentarily diminishes the distance between flame and burner; but so soon as the little drop of alcohol is burned, the original distance is again assumed. According to a recent investigation of F. Benevides *, the flame of strongly compressed coal-gas allowed to issue into the air, is separated by a space of several centimetres from the orifice of the tube whence it issues. If the pressure amount to two atmospheres, and the tube be 45 centims. in length and 4 to 9 centims. in width, the distance between the orifice of the tube and the flame amounts to about 4 centims. Benevides found the temperature of the dark space to be very low, which is only what one would expect.

The same author noticed that a flame brought near to the dark space was carried along by the stream of gas. This he regarded as proof of the dilution of the gas with air, caused by the surrounding atmosphere being carried along with the gas-stream which issued from the exit-tube with considerable velocity. If a wire be placed in the flame and be moved backwards through the dark space, the flame also moves backwards towards the burner, but returns to its original position immediately the wire is removed.

Benevides looks on these facts as justifying the conclusion that the formation of the dark space is due to the mechanical action of the issuing gas, whereby the air is driven aside for a certain distance from the orifice of the exit-tube; in this space the requisite amount of oxygen is therefore not obtainable by the gas, which consequently remains unburned. If the exit-tube be very narrow and the velocity of the issuing gas be great, the pushing back of the air may become so intense as to render combustion impossible; the flame is therefore extinguished.

I cannot profess to be satisfied with these explanations. I cannot yet understand how the existence of the flame becomes impossible on the ground that the oxygen is driven back by the gas, and at the same time that the flame is extinguished through want of oxygen. Such a condition is found *in the interior of every ordinary flame*, not in the flame of compressed coal-gas only, and is recognized as the cause of the low temperature of the interior of a flame, and of the fact that the flame forms a hollow cone of glowing gas. This driving away of air occurs throughout a proportionately small space only, and on the *outer margin* of this space the chemical combinations constituting combustion take place. These facts are so elementary that it would have been superfluous to mention them, were it not that Benevides has constructed a theory without taking them into consideration. From the following passage one would derive a singular idea of the nature of flame; for if the phrase "l'action mécanique du gaz

* *Ann. de Chim. et de Phys.* [4] xxviii. 358.

sur la flamme" &c. be not taken in a figurative sense, Benevides appears to regard the flame as a separate substance which is carried along by the stream of gas:—" Lorsque l'on introduit un solide, par exemple un fil métallique, on oppose une résistance au mouvement du gaz, dont la vitesse diminue et par conséquent, l'action mécanique du gaz sur la flamme qui tend à la projeter à distance diminue aussi, d'où il résulte que l'espace obscur diminue, et le jet lumineux se rapproche du chalumeau."

In opposition to this theory it must also be remembered that extinction of the flame could not be caused by the gas-stream driving back the air, because combustion would always be possible at the line of contact between gas and air. Outward and inward diffusion would continuously tend to increase the magnitude of the space where combustion was possible. It is therefore quite impossible that the space noticed by Benevides between the burner and the flame of compressed coal-gas could be caused by the absence of oxygen, the oxygen having been driven away by the stream of issuing gas. By this removal of oxygen the inner cold portion of the flame would be increased in size; and the flame itself would be lengthened by the increased velocity of the gas-stream; but extinction could not be brought about at the outer limits of the flame-mantle, as was noticed by Benevides.

The mechanical action of a rapid stream of gas upon the air would also only cause an increase in the size of the flame, but no removal of that flame from the burner. I believe that one cause of this removal is to be found in the *absorption of heat* occasioned by the gas issuing with so considerable a velocity, but that a second cause is also at work, viz. the relation between velocity of the gas-stream and velocity of propagation of combustion—a circumstance which Benevides overlooked in his theory, although he had apparently noticed it in his experiments.

The cooling action exercised upon the lowest portion of the flame by the quick inrush of gas may be divided into two parts. The temperature of the cylindrical flame-layer formed nearest to the burner is lowered by the coal-gas in the same manner, although to a smaller degree (on account of the low conductivity of gas for heat), as when a metallic rod is held in the flame.

The innermost portion of the burning layer, consisting of coal-gas and air which has diffused inwards, may by this means be cooled to such an extent as to be extinguished; in other words, the ignited layer may be carried further from the point where the gas issues, and an unburned mixture of gas and air may take its place.

But besides this cooling action exercised by the gas itself, the temperature of the flame suffers diminution by means of the action of the cold air surrounding the stream of gas. The air which the issuing gas carries along with it not only tends to withdraw heat from the outer portions of the flame, but penetrates also into the flame-mantle, the temperature of which it therefore diminishes.

Such withdrawal of heat by means of the cold gas, and by means of admixed air, takes place in every flame, even when burned under small pressure; but the action of these two causes, especially of the latter, increases as the velocity of the gas-stream increases; and if this be great and the gas be also under high pressure, the flame may be so cooled in the neighbourhood of the burner as to be extinguished, and a mixture of air and unburned gas may be formed and carried forward on the surface of the issuing gas-stream. In this case the existence of a flame will become possible only at a considerable distance from the burner, where the velocity of the gas has diminished, and where therefore the ignited gas is not so greatly cooled.

By increasing greatly the velocity of the gas and by diminishing the orifice through which the gas issues, it may be possible to prevent the stream of gas from becoming ignited at all—as, for instance, it is possible to extinguish the flame of a gas issuing from a burner with a small velocity, the stopcock being partially closed, by fully opening the stopcock and so increasing the rush of gas.

The explanation of this extinction of the flame is to be found in the fact that the space between burner and flame is increased by cooling the gas, and that in this space an excess of air finds its way into the gas-stream, which, as it increases its distance from the burner, becomes more and more diluted with air, until at last the mixture cannot be caused to ignite. If the orifice be small this state of affairs is attained the sooner, because under such conditions the diameter of the stream of gas is small, and the gas therefore quickly becomes diluted with air. If the explanation which has been given of the fact that a rapid stream of gas burns only at some distance from the orifice whence it issues be true, it follows that the distance between burner and flame must be decreased by raising the temperature of the gas previously to its leaving the burner. I have been able to prove that this is the case by making use of the flame of alcohol-vapour already described.

A thin platinum tube, the length of one's finger, was attached to the glass exit-tube at which the alcohol vapour was burned. The alcohol was boiled, so that a space of 2 or 3 centims. intervened between the flame and the orifice of the tube. The platinum tube was then heated by means of a Bunsen's burner held not too near to the issuing vapour, whereupon the distance between flame and burner gradually diminished until the two were in contact. On removing the Bunsen's lamp the original distance was quickly regained.

If the stream of gas be very rapid, the experiment carried out as just described does not succeed, because the temperature of the vapour in the tube is not sufficiently raised. I do not doubt that, in the experiment described by Benevides, the distance between flame and burner would be greatly diminished, if not actually removed, by passing the compressed gas through a long tube maintained at a full red heat before igniting it.

Although the explanation which I have given of the fact that a space is noticed between flame and burner in the case of quickly moving gases has taken into account all the points which have been observed, and although I have not found any facts opposed to this explanation, yet I must confess that I am scarcely altogether satisfied with it. Thus the fact that the approach of a small flame to the orifice whence the burning gas issues causes a diminution in the size of the observed space, is not to be set down so much to the decreased withdrawal of heat by the issuing cold gas (as was the case in the experiment with the heated platinum tube*), but much more to the carrying over of the combustion to the heated part. I cannot look upon the cooling actions described above as alone sufficient to cause all the observed circumstances.

The *second* explanation already given of the cause of the observed space in the case of compressed gases takes into account the relation existing between the velocity of the gaseous stream and the velocity of propagation of combustion.

In order to gain a clear idea of the action of this factor, let us suppose that the flame of a compressed gas issuing from a tube is separated by a distance of several centimetres from the orifice of the tube. The question suggests itself, Why does not the flame make its way backwards towards the burner? or, in other words, Why is not the combustion propagated backwards throughout the line of contact of gas and air towards the burner?

The gaseous stream is evidently surrounded by a zone consisting of a combustible mixture of air and gas molecules (I use this expression on account of its shortness). As soon as the temperature of a pair of molecules in one part of the zone is raised to the ignition-point by means of a flame brought near, chemical action occurs (combustion), and so much heat is thereby evolved as suffices to raise the temperature of the

* *Suprà*, p. 17.

neighbouring pair of molecules likewise to the ignition-point. This action is propagated throughout the mass, and continues so far and so long as the combustible mixture extends.

Such a process takes place in the combustion of all substances, whether solids, liquids, or gases; and to this propagation of combustion is due the continuity of all flames.

Now, inasmuch as the gas existing between flame and burner in the cases noticed clearly consists of such a combustible mixture (which may be proved in the case of alcohol vapour by bringing a small flame to the orifice of the tube), it follows that the heat given out by the last pair of molecules actually undergoing combustion must act, in the manner described, upon the pair next them, and so on throughout the gaseous mixture; yet this does not appear to be the case. I say does not *appear* to be the case, because we are too liable to look on the flame as something having an existence of its own (see Benevides), and not to regard it as *a part of the gaseous stream, which is visible to us for a short distance.*

If we may forget for a moment the true nature of the gas, we might compare the burning stream to a rod placed in a fire, which glows in the central parts, the ends emitting no rays of light. In a magnesium lamp the metallic wire is kept in motion by means of clockwork: the position of the flame is thus maintained constant. If the wire is pushed out too quickly or too slowly, the flame is advanced or withdrawn; and a constant position is only maintained by moving out the wire at that rate at which the flame would recede were the wire immovable.

This recession of the flame is conditioned by the propagation of the ignition; it becomes more rapid the higher the temperature of combustion and the lower the temperature of ignition of the combustible body. Thus a stick of phosphorus ignited at one end, and placed in a horizontal position, burns almost at once throughout its entire surface; a longer period elapses before the ignition of a wick impregnated with petroleum is propagated throughout the length of that wick; and if rape-oil be used instead of petroleum, the rate of propagation of ignition is yet slower.

Besides the difference between ignition- and combustion-temperature, two other points must be noted as conditioning the velocity of propagation of ignition: these are, the specific heat and the conductivity for heat of the burning body *.

So far as these are concerned, the withdrawal of heat from the issuing gas and admixed air is a circumstance which may

* The magnitude of the surface and the diameter are of consequence; but these may be eliminated by parallel trials.

be eliminated and which may be looked on as immaterial. But even without this, parallel experiments might lead to the discovery of interesting relations existing between the velocities of ignition and the combustion-temperatures of different combustible bodies.

For solid bodies (magnesium for instance) the velocity of propagation of ignition is equal to the velocity with which a wire of the substance must be moved forwards in order that the position of the flame may remain constant. The time required for the flame to travel to the end of a wire of known length might also be determined.

Easily combustible liquids might be placed in a hollow, and the time which expired between the ignition of one end of the liquid and the arrival of the flame at the other end noted. Liquids which burn only when absorbed by wick, might be so absorbed by wicks of known length, and the time required for the flame to travel throughout the length of the wick placed horizontally might be determined.

By the aid of such experiments a comparative quantitative expression for the liability to ignition of various combustibles might be gained.

For gases, the velocity with which the gas must issue in order to maintain a constant distance between burner and flame might be determined; or the distance might be measured, the velocity of issue being maintained constant. In order to do away with the changing velocity of different gases for the same distance from the burner (depending on the nature of the gas itself), it would be better to measure that velocity which is just sufficient to remove the flame from the burner.

I am here reminded of Bunsen's method for determining the velocity of ignition in the mixed gases evolved in the electrolysis of water *. The explosive mixture was burned at a small orifice of known area, the velocity with which the gas issued being gradually diminished by reducing the pressure until the flame passed backwards through the opening and ignited the mass of the gaseous mixture.

This point must be reached when the velocity of the issuing gas is an infinitely little less than that with which the ignition is propagated forwards.

Bunsen calculated the velocity of propagation of ignition, C, from the formula $C=\frac{4V}{\pi d^2 t}$ where V denotes the volume of gas issuing in t seconds, and d the diameter of the opening. In the case of the mixed gases from the electrolysis of water C was found to be equal to 34 millims. per second, while for

* Pogg. *Ann.* cxxxi. 165.

an explosive mixture of carbonic oxide and oxygen C was equal to less than 1 millim. per second.

These numbers cannot be made use of in the determination of the rate of propagation of ignition of a gas burning in air, inasmuch as in this case the admixed nitrogen and the abnormal conditions under which the combustible gas is mixed with air greatly diminish the rate of propagation.

In order to render clear the relations existing between the rates of issue and of propagation of ignition in the case of rapid gas-streams, the following considerations will be serviceable.

A burning gas obeys the law that the position of the base of the flame remains fixed when the rate of propagation of ignition is equal and opposite to the rate of issue of the gaseous stream. The latter is greatest close to the orifice of the burner, and decreases as this point is receded from, because of the opposition offered by the surrounding air. At all points where the velocity of the gas is greater than the velocity of propagation of ignition, the flame cannot exist of itself, because each gas-molecule will be carried to a point further than that to which the ignition is transmitted in the same time.

If, on the other hand, the rate of propagation of ignition is greater than the rate at which the gas-stream moves, the base of the flame will be driven back against the burner and will remain stationary at that point where the two velocities are exactly equal.

If a burning body be brought into the stream of gas, issuing under high pressure, at a *considerable distance* from the burner, the flame which is produced moves back against the stream of gas until it reaches the point defined above, where it remains stationary; if, however, the gas be ignited at the opening of the burner, the flame is carried along with the stream until the same point is reached. If the velocity of the gas-stream be increased, the flame moves further from the burner; if the velocity be diminished, the flame approaches the burner; and the flame rests quietly upon the burner only when the two velocities are equal, or when the velocity of propagation of ignition is greater than that of the issuing gas. The last-named condition holds in our ordinary luminous flames, the small distance generally noticed between flame and burner, or wick, resulting from the cooling action of the surroundings of the flame. The phenomena just described may be noticed in the flame of alcohol vapour issuing from an orifice with considerable velocity, as already described. If air be blown through benzol and a light be then brought to the mixture, a flame is produced which moves backwards or forwards as the velocity of the gaseous mixture is increased or diminished. The same phenomenon may be well shown by passing carbon dioxide through ether contained in a vessel surrounded with warm water, and igniting the issuing mixture. The distance between flame and burner may, in this experiment, be altered either by altering the velocity of the stream of carbon dioxide, or by warming or cooling the vessel containing the ether.

Or the mixed gases may be caused to issue from a small balloon furnished with an exit-tube and stopcock: by slightly altering the pressure by means of the hand, the flame may be caused to move backwards or forwards; or it may be maintained in a constant position. If the exit-tube be of platinum, the flame may be caused to rest upon the orifice of this tube by heating the tube with a Bunsen's burner. Such flames then behave in a manner exactly analogous with that observed in the case of rapid streams of gas; and the explanations already given of the observed distance between flame and burner can be predicated of these flames, although diluted with carbon dioxide &c.; for the decrease in velocity of the gas is compensated for by the increase in the proportion of indifferent gases. The temperature of the flame is therefore low, and the withdrawal of heat by the indifferent gases considerable. The second explanation given of the distance between flame and burner, depending upon the different velocities of the gaseous stream and of the propagation of ignition, holds good in the case of these flames.

One might be disposed to raise the objection that in these experiments the gaseous mixture was not strongly compressed, and therefore did not issue with any great velocity. But it has been shown that the greater distance between flame and burner is a function of the difference of velocities of the gaseous stream and the propagation of ignition; and in the foregoing cases the latter must be very small, because the temperature of the flame is very low, and the molecules of carbon dioxide interspersed between the molecules of the combustible gas must carry away heat from the latter. In these flames, for the reasons just stated, the rate of propagation of ignition is small and is easily exceeded by the velocity of a comparatively slowly moving gas-stream, whence results the great distance between flame and burner. This explanation is rendered more probable by considering that experiment in which the distance spoken of was diminished by warming the ether through which carbon dioxide was passed.

Inasmuch as the volume of diluting gas was here proportionally diminished, the temperature of the flame was increased; the rate of propagation of ignition was also increased, and therefore became equal to the velocity of the issuing gas at a point nearer to the burner than that at which these two velocities were previously equalized.

The diminution in the distance between flame and burner which was observed to take place in every case when the burner was heated, or when a wire was introduced between the flame and burner, must now be commented upon in the light of the second explanation already detailed. It is easy to understand why the distance in question should be diminished by heating the burner.

This distance depends upon the difference between the velocities of the gas and of the propagation of ignition; and the latter is itself a function of the difference between the ignition and combustion temperatures.

The combustion-temperature is high because of the gas being heated previously to ignition; the gas has been already heated *nearly* to its ignition-temperature. These two circumstances necessarily cause a considerable increase in the rate of propagation of ignition; the velocity of ignition becomes greater than the velocity of the issuing gas; and the distance between flame and burner is therefore diminished or entirely removed. The diminution in this distance which is brought about by holding a metallic wire between the flame and the burner, and moving the wire towards the latter, may be thus explained:—The flame-mantle is produced immediately behind the wire because the latter serves to shelter the flame from the cooling influence of the quickly rushing stream of gas. The heat so produced is communicated to the nearest portion of non-ignited gas, and the flame is thus caused to travel backwards towards the burner.

The familiar phenomenon of the flame of a petroleum-lamp burning above the slit in the piece of thin metal which surrounds the wick, is explicable on similar grounds. The flame is so cooled by the metal, at a small distance from the wick, as to be extinguished; but the lower part of the petroleum-gas still continues to burn. A mixture of unburned petroleum-vapour and products of combustion of this vapour, therefore passes upwards through the slit. This mixture may be ignited by properly regulating the screw which raises the wick; but the flame only appears at the distance of a few centimetres above the metallic cap. The velocity of ignition is very small, inasmuch as the combustible matter consists of heavy, easily condensable vapours, which are moreover greatly diluted by the products of combustion of the lower part of the gas, viz. by carbon dioxide and water, substances having high specific heats. The distance between the metallic cap and the upper flame may be still further increased by cooling the combustible vapours. The following experiment is instructive :—

A glass tube, 8 to 10 millims. wide and about 10 centims. long, is fastened vertically in the middle of the slit in the metallic cap surrounding the wick of a lighted petroleum-lamp. By raising the wick a thick white vapour may be made to issue from the upper orifice of the glass tube. If this vapour be ignited, a small flame is produced, which plays above the smoke at a distance of perhaps 10 centims. from the tube. The products of combustion present above this flame are invisible, because the combustion is complete and the water which is produced is dissipated by the heat evolved.

If the column of visible vapour between the tube and the small flame be carefully observed, it is seen to be rendered transparent by the action of the heat radiated from the lower flame, and finally to become ignited. In this way the fact may be explained that the small flame does not rest directly upon the visible column of vapour, but is separated from it by a transparent space 1 or 2 millims. in extent. If the glass tube in this experiment be replaced by one made of platinum, and if this be heated, the small flame may be caused to approach and finally to rest upon the orifice of the platinum tube.

The column of smoke which is seen to issue from a petroleum-lamp burning without the glass cylinder, is caused by the cooling action of the metallic cap which surrounds the wick. The flame-mantle impinges upon this metallic cap, is thereby held back, and so is rendered unfit for propagating the ignition upwards. The lower flame, being fed by air entering from below, continues to burn, and produces new gases and vapours from the oil-saturated wick, performing, therefore, a part similar to that of the retort-fires in the manufacture of coal-gas.

As the metallic cap gets heated, the cooling action which it exercises upon the stream of ascending vapours diminishes, and the distance separating the upper flame from the lower is decreased. If the metallic cap be heated by a Bunsen's lamp, this distance becomes very small, and entirely disappears when the cap begins to glow. If a cap already heated to redness be placed upon a lighted and properly adjusted lamp, the flame does not become separated at all.

Everyday experience tells us that placing a glass cylinder upon the lamp causes the two flames to unite. The diminished supply of air brings about an elongation and curtailment in the dimensions of the flame, whereby it no longer touches the sides of the metallic cap; at the same time the flame-temperature is increased, and the motion of the heated particles of gas is accelerated. These circumstances act in opposition to the cooling effect of the metallic cap.

These experiments may be interpreted as pointing to the withdrawal of heat from the sides of the stream of gas and air as the cause of the space noticed between flame and burner; but it has been shown that this action is but small, and that the superior velocity of the stream of gas over that of the propagation of ignition is the principal cause of the observed effect. Whether this be the sole cause cannot be determined until further experiments have been carried out.

The most important points established in the foregoing part of this paper may be summarized thus:—

1. The fact that a gas-flame does not rest upon the burner nor a candle-flame upon the wick, as also the fact that a flame never directly touches a cold body held within it, is to be explained by the cooling action exercised upon the gas by its surroundings.

The combustible gases are cooled throughout a definite space below their ignition-temperature; the flame is therefore extinguished. This conclusion is opposed to that of Blochmann.

2. The very considerable distance noticed between the burner and the flame of a gas issuing under high pressure, or mixed with a large volume of an indifferent gas, cannot be accounted for on the grounds put forward by Benevides. The production of such a distance is much rather to be traced to the cooling action of the stream of gas and of the outer air, and perhaps more especially to the fact that the velocity of the stream of gas in the neighbourhood of the burner is greater than the velocity of propagation of ignition within the gas.

3. In order that other circumstances conditioning the effect may be removed, the velocity of propagation of ignition must be *equal* to that of the gas-stream at the point, situated some distance from the burner, where the flame begins.

Determinations of the velocity of ignition should be made under these conditions for different gases; and since this magnitude is a function of the difference between ignition and combustion temperatures, conclusions may be drawn from such experiments regarding the relations existing between these points *.

* Since going to press, I have noticed an interesting paper by E. Mallard [*Annales des Mines*, 1875, iii. 355], in which the velocity of

4. The velocity of propagation of ignition may be easily determined for solid and liquid combustible bodies; and the numbers so obtained may be regarded as comparative quantitative expressions for the liability to ignition of these substances.

II. *Description of a Large Induction-coil.* *By* William Spottiswoode, *F.R.S.*

To the Editors of the Philosophical Magazine and Journal.

Gentlemen,

Although I have not as yet many experimental results sufficiently complete for communication to your Magazine, I still think that the construction of an induction-coil capable of giving a spark 42 inches in length is an instrumental feat deserving of record in the annals of science. I therefore venture to submit the particulars of this coil, recently completed for me by Mr. Apps, of 433 Strand, to whose skill and perseverance the success of the undertaking is due.

The general appearance of the instrument is represented in the following figure, by which it is seen that the coil is supported by two massive pillars of wood sheathed with gutta-percha, and filled in towards their upper extremities with paraffine wax. Besides these two main supports, a third, capable of being raised or lowered by means of a screw, is placed in the centre, in order to prevent any bending of the great superincumbent mass. The whole stands on a mahogany frame resting on castors.

The coil is furnished with two primaries, either of which may be used at pleasure. Either may be replaced by the other by two men in the course of a few minutes. The one to be used for long sparks, and indeed for most experiments, has a core consisting of a bundle of iron wires each ·032 inch thick, and forming together a solid cylinder 44 inches in length and 3·5625 inches in diameter. Its weight is 67 lbs. The copper wire used in this primary is 660 yards in length, ·096 inch in diameter, has a conductivity of 93 per cent., and offers a total resistance of 2·3 ohms. It contains 1344 turns wound singly in 6 layers, has a total length of 42 inches,

ignition of explosive mixtures of hydrocarbons and air is measured by Bunsen's method. The maximum velocity for marsh-gas and air was 0·524 millim., the minimum 0·041 millim. per second. The numbers for coal-gas and air were—maximum 1·01 millim. and minimum 0·097 millim. per second. The velocities are in these instances very slow; and the experiments show that they are still further reduced by an excess of either constituent of the mixture.